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THE EFFECT ON RESPIRATORY DEAD SPACE
OF PROLONGED EXPOSURE TO A SUBMARINE ENVIRONMENT

by

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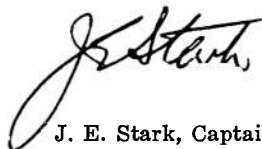Research Work Unit MF12.524.006-9028.02

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SUMMARY PAGE

THE PROBLEM

To determine whether prolonged exposure to elevated levels of CO_2 in a submarine environment results in an increase in the respiratory (physiological) dead space as previously established in a laboratory experiment.

FINDINGS

Although the studies are very limited in scope, the results are consistent in the demonstration of an abnormally high respiratory dead space during patrols. This change is shown to be transitory in nature. Six of the ten subjects participated in both patrols. Their physiological dead space values returned to control values eight weeks after the patrol, showing that the effect is reversible. Smoking habits and length of service in submarines did not change this response.

APPLICATIONS

This report will be valuable for all submarine medical officers, students in the School of Submarine Medicine and individuals interested in research in submarine medicine.

ABSTRACT

Measurements were made of arterialized capillary carbon dioxide tension and mixed expired carbon dioxide as well as respiratory minute volume, tidal volume and respiratory frequency on 10 subjects during control periods and following 20 days of exposure to submarine atmosphere on two patrols. The physiological dead space was found increased by 60% on the first patrol, and 61% on the second patrol, in which the average CO_2 concentrations were, 0.8% and 0.9%, respectively. These findings correspond with previous observations obtained under laboratory conditions, showing a 62% increase in physiological dead space, following 40 days of exposure to 1.5% CO_2. Six of the same ten subjects on the second patrol had also served on the first patrol. Their physiological dead space returned to control values after the patrol showing that the effect is reversible. Smoking habits and length of service on submarines did not change either control values of physiological dead space or the values obtained during the patrols. The significance of these findings for the evaluation of the health hazards of prolonged exposure to the submarine atmosphere is discussed.

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INTRODUCTION

Respiratory adaptation to carbon dioxide (CO_2) has been shown in laboratory tests to include, among other effects, an increase of 62% in respiratory dead space after 40 days of exposure to 1.5% CO_2.[1] During the subsequent recovery period on air, the physiological dead space returned to control values.

This report concerns a study made aboard an operating nuclear submarine to determine whether similar results would be found. The concentrations of carbon dioxide found in such a submarine are in the neighborhood of one per cent[2, 3]. Ten subjects were studied prior to and during two patrols, to determine whether changes in physiological dead space would occur.

MATERIALS AND METHODS

The following measurements were made, first under normal conditions, and then at sea after about 20 days of continuous exposure to average daily carbon dioxide levels of 0.91% during the first patrol, and 0.79% CO_2 during the second patrol: breathing frequency in breaths/minute, tidal volume, minute volume, mixed expired percentage of CO_2, arterialized venous partial pressure of CO_2 and blood pH.

The experimental protocol was as follows:

In the control period prior to first patrol, measurements were taken with the subjects supine, whereas on patrol in rough seas and with limited space in the sick bay, the measurements were taken in a sitting position. A correction factor used for converting the supine control measurements to equivalent sitting values was based on studies of Larson and Severinghaus[4]. After the subject accustomed himself to a two-way inspiration/expiration valve with a pliable rubber mouthpiece, a 100-liter Douglas bag was attached so as to collect any expired air over a ten minute period during which the average respirations per minute were noted.

The volume of the expired air was meas-ured with a dry gas meter and the expired CO_2 concentration was determined with an infrared CO_2 analyzer (Beckman LBL 1) on three occasions, except during the first patrol, where measurements were made with a Harvard Series 2000 CO_2 analyzer.

Blood P_{CO2} and pH was measured with an Ultra-Micro pH/Blood Gas Analyzer, 113 S1 (Instrumentation Laboratories, Inc.). During the first patrol a Radiometer Micro Blood Gas Analyzer and Tonometer were used.

The ten minute volume of collected expired air was corrected to Body Temperature Pressure Saturated (BTPS), and the average tidal volume was determined by dividing the ten-minute corrected expired volume by the total number of respirations over the 10-minute period.

The investigations were repeated during a second patrol and, in this case, both control and patrol measurements were made in a sitting position. Moreover, six subjects participated in both studies, allowing an evaluation of recovery between patrols. The actual blood pH values and the blood P_{CO2} values were determined on arterialized capillary blood samples. Gambino, et al.,[5] have shown that arterialized capillary blood can be substituted for the arterial blood sample, giving equivalent results. The physiological dead space ($V_{D_{PHY}}$) was calculated according to Enghoff[6], as follows:

$$V_{D_{PHY}} = \frac{V_E\ (Pa_{c_{CO2}} - P_{E_{CO2}})}{Pa_{c_{CO2}} - P_{I_{CO2}}}$$

where:

$V_{D_{PHY}}$ = physiological dead space

V_E = tidal volume (expiratory)

$Pa_{c_{CO2}}$ = arterialized capillary CO_2 pressure

$P_{E_{CO2}}$ = mixed expired CO_2 pressure

$P_{I_{CO2}}$ = inspired CO_2 pressure

RESULTS

Table I presents the data on respiratory functions collected on 10 subjects during control periods and during 20-day exposure to submarine atmosphere. Respiratory minute volume, tidal volume and respiratory frequency did not exhibit consistent changes, however, the blood P_{CO_2} tension and physiological dead space were found significantly increased during the patrols.

Six of the subjects participated in both patrols. Their data are shown in Table II. The second set of control measurements actually represent data obtained after two months of recovery following the first patrol. It is therefore possible to evaluate whether the physiological dead space returned to normal during the period between two patrols which it does, as indicated in Table II.

Since the length of submarine service might produce some differences in the changes in physiological dead space, a group of three submariners, with average submerged time of 19.3 months, was compared with the other seven submariners having an average submerged time of 4.9 months. As can be seen in Table III, control, as well as patrol values, were nearly the same in both groups.

Smokers and non-smokers do not show any differences in their control values as well as in their response to the exposure to the submarine environment, as shown in Table IV.

DISCUSSION

The blood P_{CO_2} control values for the first and the second patrol are rather low, particularly the supine control data which should be higher. Both sets of control data probably reflect some hyperventilation of the submariners carrying out a test in the unfamiliar laboratory setting. This means that the dead space measurements during control condition are most likely too low. However, since they are still in the range of normal values, they cannot be too far off. On the other hand, the data obtained during the patrols show a consistent increase in P_{CO_2} as well as physiological dead space. The physiological dead space data during patrol are significantly higher and out of normal range. If the subjects had hyperventilated during patrol, the dead space should be lower.

In spite of the obvious limitation of this study, consisting of only one measurement during the patrol and the hyperventilation problem during the control period, the consistency of the findings demonstrating abnormally higher physiological dead space values makes them significant, particularly since they represent the first data obtained under these conditions. It is obviously necessary to expand this work and to include far more frequent measurements during patrol.

TABLE I

EFFECT OF 20 DAYS EXPOSURE TO SUBMARINE ATMOSPHERE ON RESPIRATORY FUNCTIONS (10 SUBJECTS)

		Respiratory rate	Tidal volume ml	Minute volume 1/BTPS	Mixed Expired CO_2%	Blood P_{CO_2} mm Hg	pH	Physiol. dead space ml (BTPS)	Corrected Physiol. dead space
Control	Mean	12.5	700	9.0	3.20	31.5	7.490	199 (supine)	232 (sitting)
	S.E.	1.7	57	1.1	.14	.8	.018	31	29
First Patrol	Mean	12.2	966*	11.4	4.0	42.4*	7.490	370 (sitting)*	370 (sitting)*
	S.E.	1.7	84	1.4	.17	1.6	.011	47	47
Control	Mean	9.7	949	9.14	3.40	32.6	——	221 (sitting)	
	S.E.	.9	70	.98	.34	.97		24	
Second Patrol	Mean	8.5	945	8.76	3.40	36.8*	——	361 (sitting)*	
	S.E.	.6	55	.23	.66	1.0		27	

*Differences from controls statistically significant at the 5% level and better.

TABLE II

CHANGES IN PHYSIOLOGICAL DEAD SPACES
DURING TWO PATROLS IN 6 SUBJECTS

Conditions	Control on air	1st Patrol 20 days of exposure to .91% CO_2	Control on air	2nd Patrol 20 days of exposure to .79% CO_2
Physiological dead space (ml)				
Mean	206.	367 *	216	369 *
S.E.	24.0	48.9	39.8	41.7

*Values obtained during both patrols were statistically significantly different from controls at the 5% level. However, there was no difference between control or between patrol values.

TABLE III

PHYSIOLOGICAL DEAD SPACE MEASUREMENTS
AND LENGTH OF EXPOSURE

		Control	Patrol
Short time	Mean	221 ml	359 ml *
Av. 4.9 months	S. E.	(±32.23)	(±36.55)
n = 7			
Long time	Mean	222 ml	366 ml *
Av. 19.3 months	S. E.	(±35.20)	(±37.00)
n = 3			

* Differences between controls and patrol values statistically significant at the 5% level. However, there is no difference between control and patrol values of subjects with short or long time submarine service.

TABLE IV

PHYSIOLOGICAL DEAD SPACE MEASUREMENTS AND SMOKING HABITS

		Control	Patrol
Smokers (any degree of smoking)	Mean	223	350 *
	S. E.	(±25.35)	(±29.42)
n = 4			
Non-smokers (no cigarettes)	Mean	220	378 *
	S. E.	(±38.06)	(±54.73)
n = 6			

* Differences between control and patrol values statistically significant at the 5% level and better. However, there was no difference in control values of smokers and non-smokers and patrol values of smokers and non-smokers.

The increases in physiological dead space found in the first and second patrol amounting to 60% and 61% agree very well with each other, Table I. The exposure time to the submarine atmosphere was the same, about 20 days. It has been assumed that the decisive factor in the submarine atmosphere causing the changes in dead space is the increased CO_2 concentration, since the latter has been shown to produce an increase in physiological dead space under acute[7] as well as under chronic exposure[1].

After 40 days of exposure to 1.5% CO_2, 62% increase in physiological dead space was observed which is the same range as the changes measured during 20 days of exposure to a submarine atmosphere containing 0.8 and 0.9% CO_2.

In both conditions the measured increase in physiological dead space was of transitory nature. Values returned to normal during the recovery periods. It is of particular importance to obtain information which can be used in an evaluation of hazard imposed by prolonged exposure to the submarine atmosphere on respiratory functions. The data obtained so far, although very limited, do not indicate the existence of a measurable hazard. This statement is based on the demonstrated transitory nature of the increase in physiological dead space, (Table II) as well as the evidence that repeated prolonged exposure to the submarine atmosphere (19.3 months) does not affect the control values of the physiological dead space and the response to the submarine atmosphere as compared with subjects exposed only for 4.9 months (Table III).

Although one could expect some changes due to the combined effects of increased carbon monoxide content of inhaled air when smoking cigarettes and the elevated CO_2 concentration in the submarine atmosphere, smoking habits (average 1 pack a day) did not produce any significant change in physiological dead space (Table IV).

The data obtained in these investigations does not allow speculation as to whether the changes in physiological dead space found during the submarine patrols were caused by changes in alveolar perfusion or ventilation.

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13. ABSTRACT

   Measurements were made of arterialized capillary carbon dioxide tension and mixed expired carbon dioxide as well as respiratory minute volume, tidal volume and respiratory frequency on 10 subjects during control periods and following 20 days of exposure to submarine atmospheres on two patrols. The physiological dead space was found increased 60 and 61% during the first and second patrols, respectively, in which the average CO_2 concentrations were 0.8 and 0.9% CO_2. The findings correspond with previous observations obtained under laboratory conditions showing a 62% increase in physiological dead space following 40 days of exposure to 1.5% CO_2. Six of the same 10 subjects on the second patrol had also served on the first patrol. Their physiological dead space returned to control values after the patrol showing that the effect is reversible. Smoking habits and length of service on submarines did not change either control values of physiological dead space or the values obtained during the patrols. The significance of these findings for the evaluation of the health hazards of prolonged exposure to the submarine atmosphere is discussed.

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